Jet Propulsion Laboratory
California Institute of Technology

NASA Small Mission Explorer (SMEX) Program: Past, Present and Future Low Costs

Michael Saing, Systems Engineer
Dr. Tony Freeman, Senior Program Manager
Jet Propulsion Laboratory

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The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Agenda

- Motivation and Objective
- History and Background of NASA's Explorer Mission
- NASA's Small Explorers
- Past SMEX mission
- Present SMEX mission
- Comparisons and findings
- Rules of Thumbs (ROT)
- Enabling Future Low Cost Explorer Missions
- Summary
- References
- Caveats
- Closing

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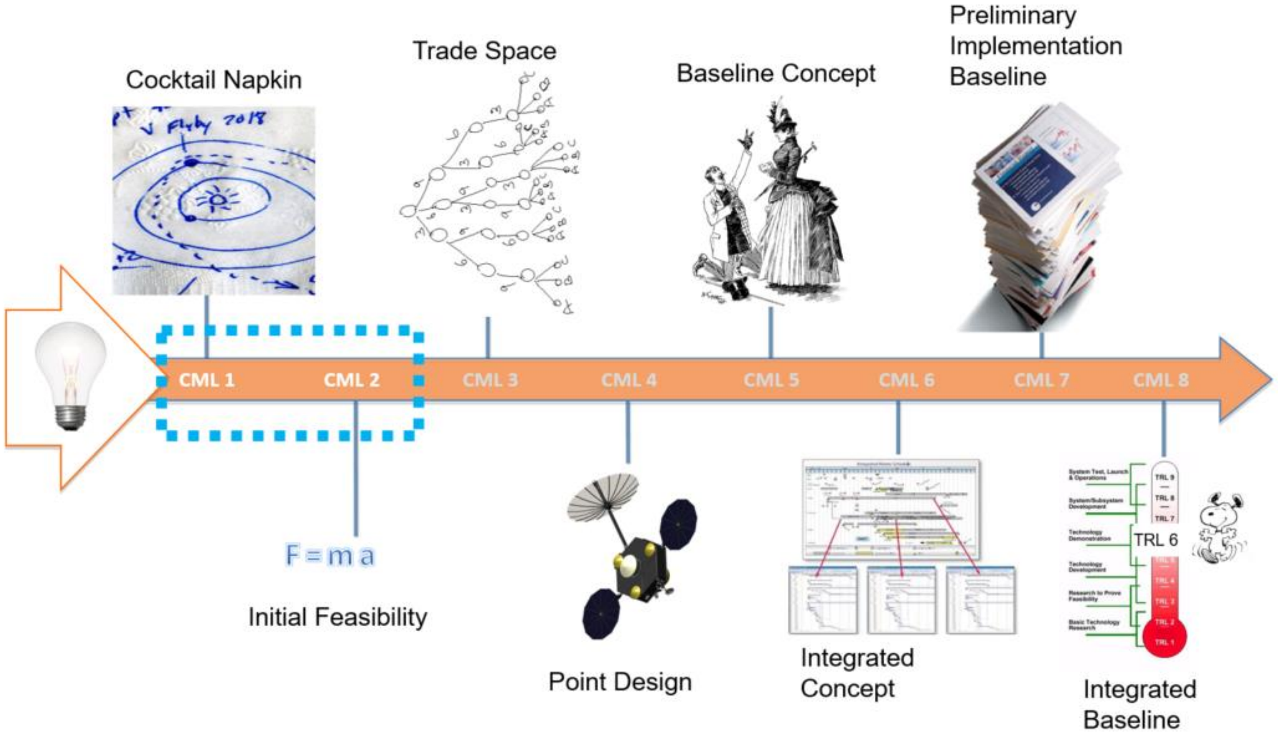
Motivation and Objective

- Explorer One - 1958
- Look into Small Mission Explorer (SMEX) program and its historic missions
- Questions to self:
  - What's the total average "low-cost" SMEX mission?
  - What's the average cost of spacecraft and instruments?
  - Changes of Cost, Mass and Power from PDR to launch?
  - What's the average "Rapid" Development Schedule for Phase B-D?
  - What are drivers for cost overruns?
  - What is considered to be "in-family" with respect to cost to previous actual missions?
- Approach
  - Gather data and inflated cost to FY18$ from NASA's CADRe available on ONCE and perform top level research and analysis on each project and compared it against each other and by mission type – Astrophysics and Heliophysics
- After research and analysis
  - Answer all or some of the questions mentioned (above)
  - Generate rules of thumbs for small satellite explorer missions
  - Understand and suggest some design space and cost trades for future small explorer missions while maintaining low cost compelling science and innovative technology in return

JPL's Concept Maturity Level (CML)

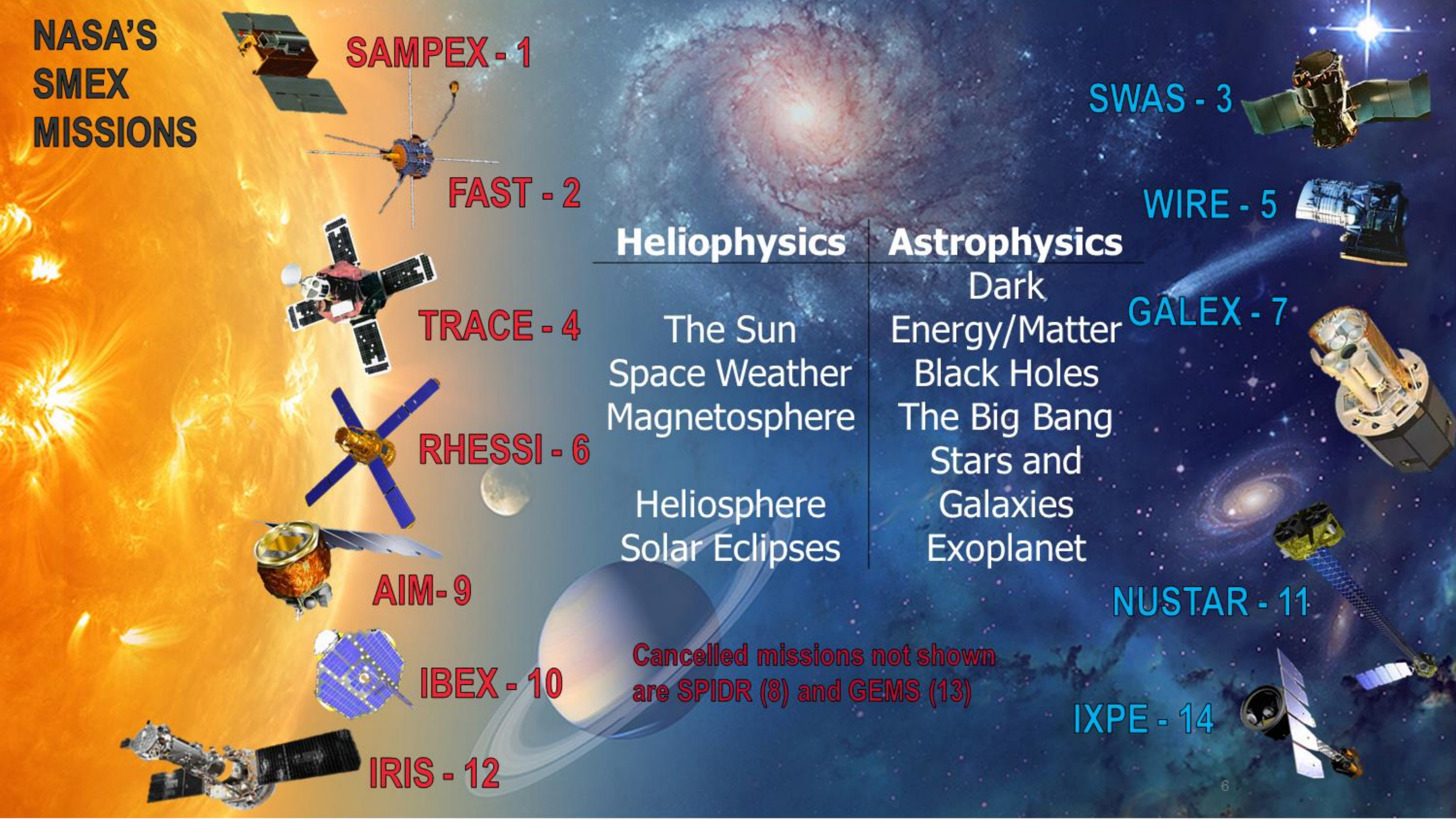


History and Background of NASA's Explorer Mission

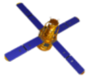
Titled: Explorer 1: First U.S. Satellite
https://www.youtube.com/watch?v=WT39gTs9X7k

Explorer 1 – Launched January 31, 1958 (60 years)
(from Left to right) Dr. William Pickering, James Van Allen, Warner Von Braun at The Jet Propulsion Laboratory

- NASA's Explorer Mission
  - Explorer-1, first explorer mission Earth and Heliophysics science mission with one instrument weighing 4.82kg to detect trapped radiation in Earth's magnetosphere (aka Van Allen Radiation Belt
  - NASA have sponsored over 50 low-cost explorer missions
  - Late 1980's/early 1990's NASA created the official Explorer Program for universities, all NASA centers, commercial industries and government labs to compete for funding
  - Three Explorer class
    - 1) Medium Explorers (MIDEX) $180M
    - 2) Small Explorers (SMEX) $120M
    - 3) Consist of two subclasses
      - 3a) Mission of Opportunities (MO) $55M
      - 3b) University Class (UNEX) $15M
  - Sponsored by NASA's SMD
  - Explorer Program managed at NASA GSFC
- More info at: https://explorers.gsfc.nasa.gov/


NASA'S
SMEX
MISSIONS
SAMPEX - 1
FAST - 2
TRACE - 4
RHESSI - 6
AIM- 9
IBEX - 10
IRIS - 12
Heliophysics
The Sun
Space Weather
Magnetosphere
Heliosphere
Solar Eclipses
Astrophysics
Dark
Energy/Matter
Black Holes
The Big Bang
Stars and
Galaxies
Exoplanet
SWAS - 3
WIRE - 5
GALEX - 7
NUSTAR - 11
IXPE - 14
Cancelled missions not shown
are SPIDR (8) and GEMS (13)
6

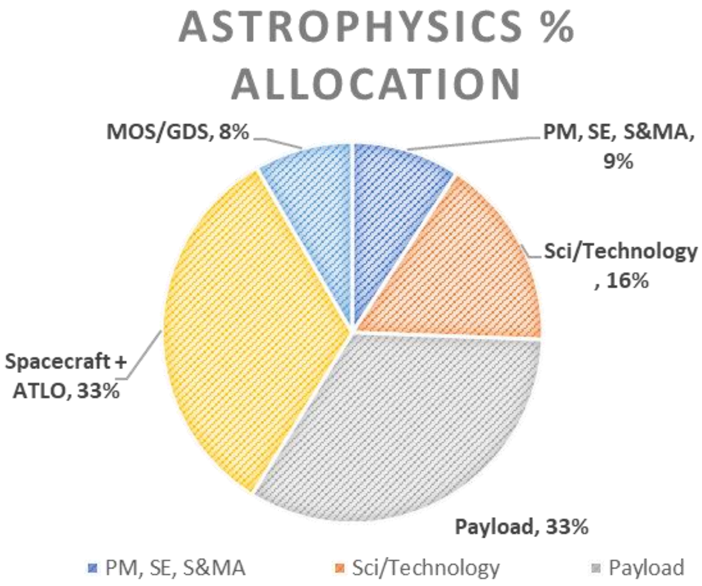
Summary of SMEX Missions 1/2

MISSION	SPACECRAFT	SMEX MISSION#	LAUNCH DATE	TYPE	PURPOSE	# OF INSTRUMENTS	INSTRUMENTS
SAMPEX Solar, Anomalous, and Magnetospheric Particle Explorer		SMEX - 1	7/3/1992	Heliophysics	Energetic particle emissions from the Sun	4	HILT (Heavy Ion Large Telescope) - measure anomalous cosmic ray charge state; electrons > 150 keV LICA (Low Energy Ion Composition Analyzer) - measure low energy ions; kilovolt electrons MAST (Mass Spectrometer Telescope) - measure solar, galactic, and anomalous cosmic ray isotopes
FAST Fast Auroral Snapshot Explorer		SMEX - 2	8/21/1996	Heliophysics	Plasma physics of auroral phenomena	5	EFPE (Electric Field Plasma Experiment) - measure electric fields. The fields signal processing spans a frequency band from DC to about 2 MHz and has a dynamic range of 100 dB ESA (Electrostatic Analyzers) - measure ion and electron pitch-angle distribution. The measured energy range is 4 eV to 30 keV for electrons and 3 eV to 25 keV for ions MAG (Magnetometer) - The search-coil magnetometer uses a three-axis sensor system that provides AC magnetic field data over the frequency range 10 Hz to 2.5 kHz on two axes while the third axis response extends to 500 kHz. TEAMS (Time-of-Flights Energy Angle Mass Spectrograph) - measure the full 3-dimensional distribution function of the major ion species (including H+, He +, He ++, O +, 02 + and NO +) during each half-spin period (2.5 s) of the spacer
SWAS Submillimeter Wave Astronomy Satellite		SMEX - 3	12/6/1998	Astrophysics	Chemical composition, energy balance and structure of interstellar clouds	1	Telescope operating in the submillimeter wavelengths of far infrared and microwave radiation.
TRACE Transition Region and Coronal Explorer		SMEX - 4	4/2/1998	Heliophysics	Three-dimensional magnetic structures which emerge through the Sun's photosphere	1	TRACE (Transition Region and Coronal Explorer) - The TRACE instrument is a high-resolution multispectral spectrometer [in the EUV (Extreme Ultraviolet) and UV(Ultraviolet) region] featuring a 30 cm diameter Cassegrain telescope (160 cm in length, 8.66 m focal length) and a filter system which feeds a CCD detector array (1024 x 1024 lumogen coated, front illuminated, three-phase CCD).
WIRE Wide-Field Infrared Explorer		SMEX - 5	3/5/1999	Astrophysics	Survey the celestial sky in the infrared bands	1	Telescope consists of the Ritchey-Chretien. WIRE was intended to be a four-month infrared survey of the entire sky at 21-27 micrometers and 9-15 micrometers, specifically focusing on starburst galaxies and luminous protogalaxies. Aperture of 30cm and resolution of 20-23 arcsec
RHESSI Reuven Ramaty High Energy Solar Spectroscope Imager		SMEX - 6	2/5/2002	Heliophysics	Image at high resolution solar flares in X-rays and gamma rays	1	RHESSI (Ramaty High-Energy Solar Spectroscopic Imager) - The objective is to obtain high fidelity color movies of solar flares in X-rays and gamma rays measure energy range of 3 keV to 17 MeV (soft X-rays to gamma-rays).
GALEX Galaxy Evolution Explorer		SMEX - 7	4/28/2003	Astrophysics	UV imaging and spectroscopic survey	1	TELESCOPE - Near and Far Ultra Violet Telescope. Ritchey-Chretien. 50 cm; Wavelengths 135-280 nm (UV)

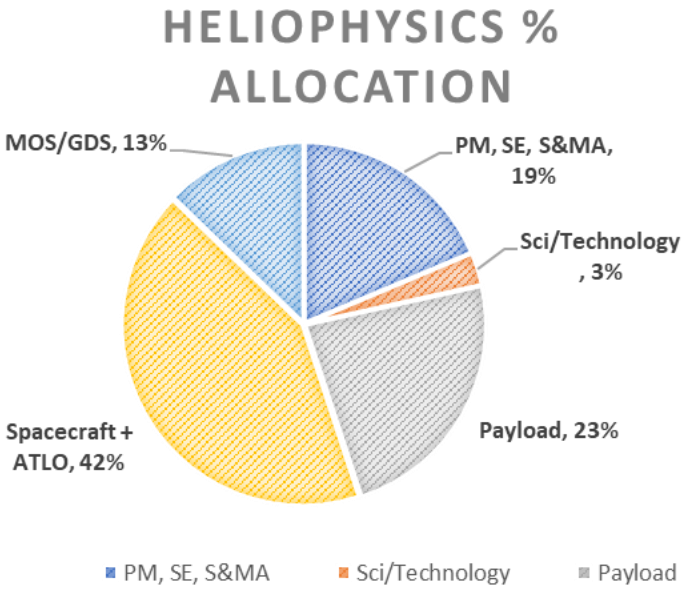
Summary of SMEX Missions 2/2

MISSION	SPACECRAFT	SMEX MISSION#	LAUNCH DATE	TYPE	PURPOSE	# OF INSTRUMENTS	INSTRUMENTS
SPIDR Spectroscopy and Photometry of the Intergalactic Medium's Diffuse Radiation		SMEX - 8	CANCELLED - Instrument Related Issues	Astrophysics	Measure the amount of hot gas found between galaxies	N/A	
AIM Aeronomy of Ice in the Mesosphere		SMEX - 9	4/25/2007	Heliophysics	Study of polar mesospheric clouds	3	CDE (Comet Dust Experiment) - The objective is to measure the influx of dust particles into the upper atmosphere, the PMC (Polar Mesospheric Cloud) region. CIPS (Cloud Imaging and Particles Size) - The objective of CIPS is to take imagery of the clouds to determine when and where they form, and to document what they look like. SOFIE (Solar Occultation for Ice Experiment) - The objective of SOFIE is to observe the following atmospheric constituents by the use of the solar occultation technique: temperature, PMCs, carbon dioxide (CO_2), methane (CH_4), nitric oxide (NO), ozone (O_3) and aerosols.
IBEX Interstellar Boundary Explorer		SMEX - 10	10/19/2008	Heliophysics	Discovering the global interaction between the solar wind and the interstellar medium	2	IBEX (Interstellar Boundary Explorer) - The IBEX payload consists of two ENA sensors and a CEU (Combined Electronics Unit). The objective of these special imagers is to detect energetic neutral atoms (instead of photons of light) to create maps from the solar system's outer edge, enabling scientists to map the boundary between our Solar System and interstellar space. The sensors measure ENAs from ~10 eV to 2 keV (IBEX-Lo) and from ~300 eV to 6 keV (IBEX-Hi)
NUSTAR Nuclear Spectroscopic Telescope Array		SMEX - 11	6/13/2012	Astrophysics	Focusing X-ray telescope in space for energies in the 8-80 keV. Range	1	Telescope - First direct imaging X-Ray telescope. Wavelength observation from 3-79 keV
IRIS Interface Region Imaging Spectrograph		SMEX - 12	6/28/2013	Heliophysics	Explore the solar chromosphere	1	IRIS (Interface Region Imaging Spectrograph) - The IRIS instrument is a multi-channel imaging spectrograph with a 20 cm UV telescope. The objective is to obtain UV spectra and images with high resolution in space (1/3 arcsec) and time (1s) focused on the chromosphere and the transition region of the sun, a complex dynamic interface region between the photosphere and corona.
GEMS Gravity and Extreme Magnetism		SMEX - 13	CAANCELLED - COST OVERRUN	Astrophysics	Measure polarized X-rays	N/A	
IXPE Imaging X-Ray Polarimetry Explorer		SMEX - 14	TBD	Astrophysics	Exploits the polarization state of light to understand X-ray production in objects (neutron stars, pulsar wind nebulae, stellar, and supermassive black holes).	N/A	

SMEX Total Lifecycle Phase A-F* By WBS**



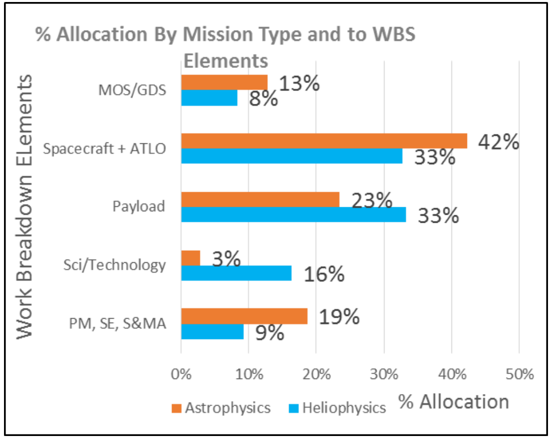
Astrophysics Missions:
GALEX, NuSTAR, SWAS, WIRE



Heliophysics Missions:
AIM, FAST, IBEX, IRIS, RHESSI, SAMPEX, TRACE

* Data shows that average breakout for Phase A-D and E/F cost is ~90% Formulation/Development and ~10% Operations
**Launch Ride/Services not included

Cost Discussion on Variances



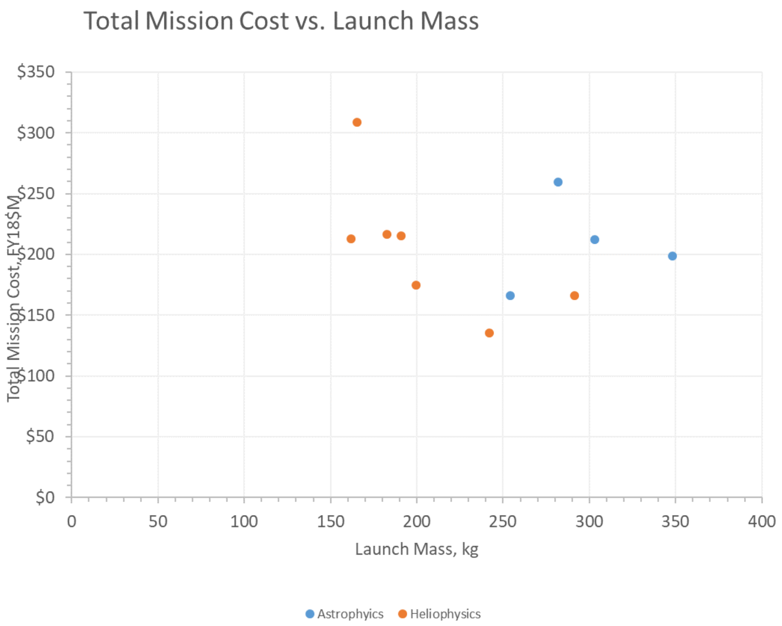
WBS #	WBS Description	Astrophysics % Allocation	Heliophysics % Allocation	Notes
1,2,3	PM, SE, S&MA	9%	19%	The number of instrument might scale down with these management wraps. Astrophysics' single telescope vs. Heliophysics multiple instruments
4	Science + Technology	16%	3%	Heliophysics has other partnerships and collaborators such as NSF, NOAA, Air Force Office of Sci. Research (AFOSR), Astrophysics usually has larger teams doing research and analysis, long sky observation time.
5	Payload	33%	23%	Astrophysics' telescopes are more expensive than heliophysics' instruments Astrophysics payload mass more than Helio by ~80% (telescope instruments has more mass – mirrors, electronics, etc…)
6,10	Spacecraft + ATLO	33%	42%	Comparison between Helio and Astro shows that: -Astrophysics S/C + ATLO costs less than Helio by ~10% (accommodation one vs multiple instruments, workforce) -Astrophysics spacecraft mass more than Helio by ~20% (mass to support telescopes typically more – primary & secondary structure, cabling, electronics, etc…)
7,9	MOS + GDS	8%	13%	This WBS is unique to each project. Depends on science plans. Cost driver for these two WBS are data latency, active customers seeking instant data when a weather event happens (Helio) or Solar event (Astro), Number of instruments, science data system (SDS) and where its bookkept (sometimes in WBS 4), and where mission ops is being done (contracted vs. government)

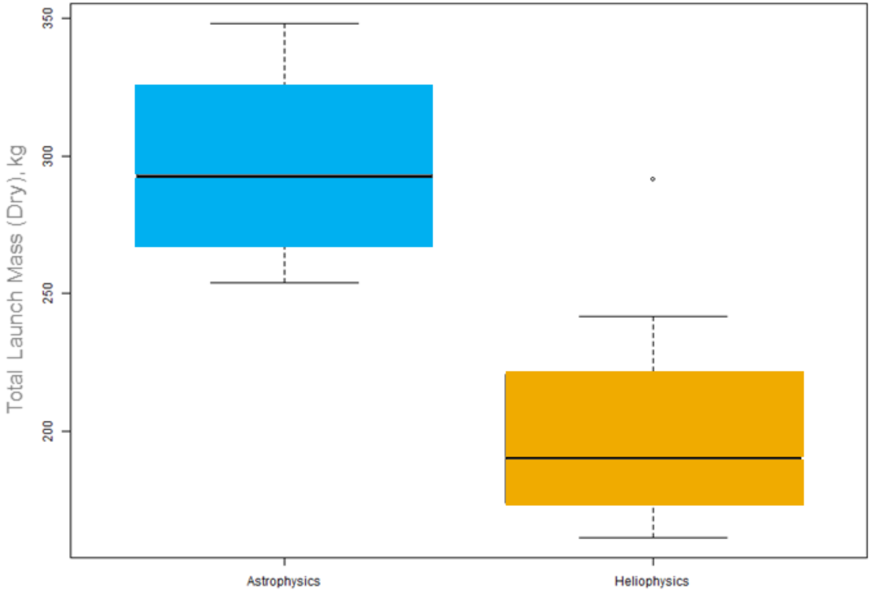
Schedule – Development and Operations

Still in Operations	SEMX Missions	Mission Type	Development B-D Duration (Months)	Planned Mission Duration (Months)	Final or Elapsed currently in operation (Months)
✗	GALEX	Astrophysics	34	29	122
✓	NuSTAR	Astrophysics	36	24	75
✗	SWAS	Astrophysics	71	24	81
✗	WIRE	Astrophysics	37	4	16
✓	AIM	Heliophysics	39	24	136
✗	FAST	Heliophysics	57	12	152
✓	IBEX	Heliophysics	33	24	118
✓	IRIS	Heliophysics	37	24	62
✓	RHESSI	Heliophysics	42	24	199
✗	SAMPEX	Heliophysics	35	36	144
✗	TRACE	Heliophysics	30	12	147

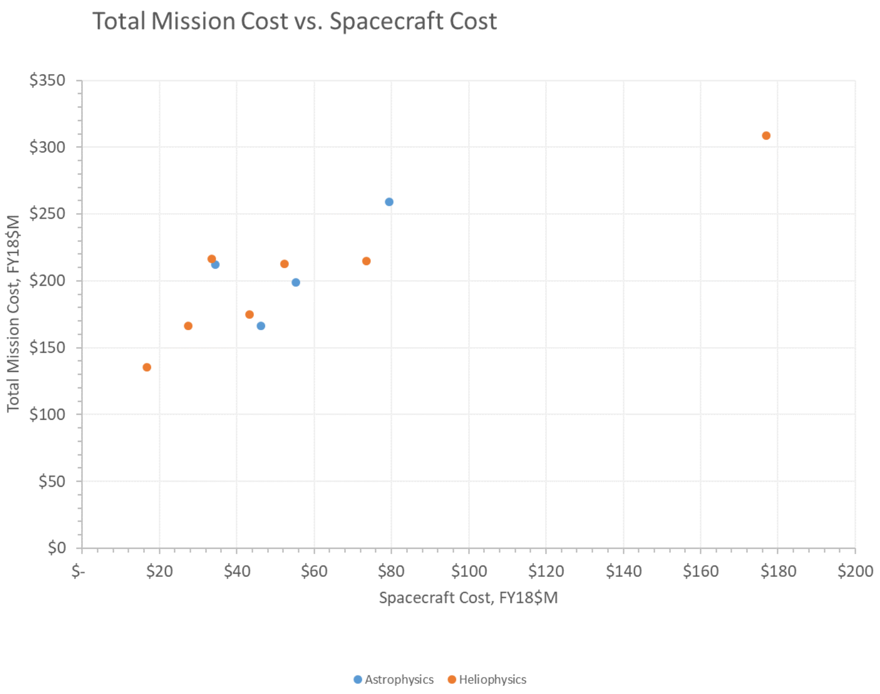
Note: WIRE - Cooler failed after lunched, but the star tracker was used to study star's oscillation and testing the concentrator system on the solar arrays which had the reflectors on them.

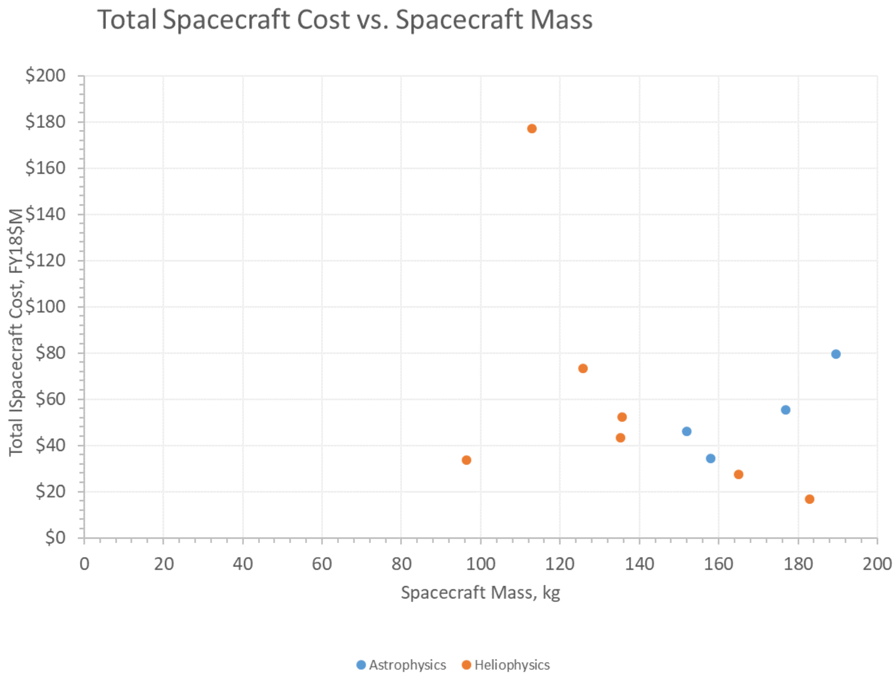
Total Cost vs Launch Mass by Mission Type



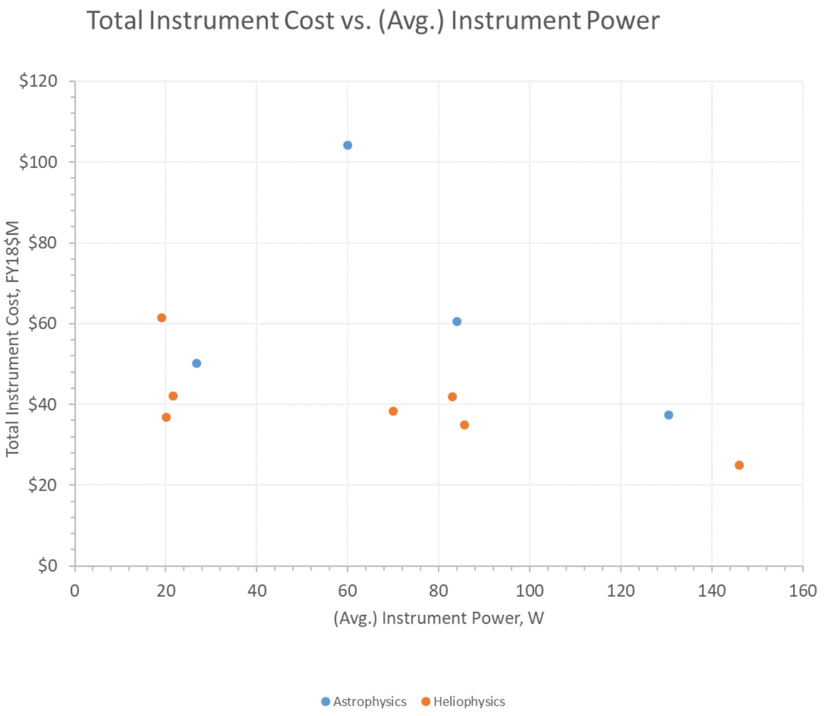


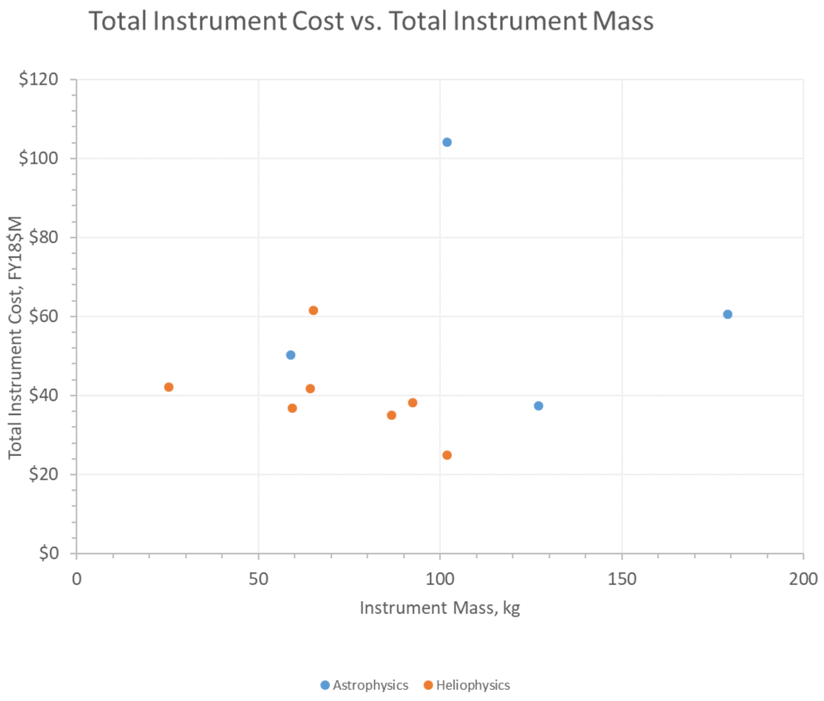
Costs vs Spacecraft and Mission Type



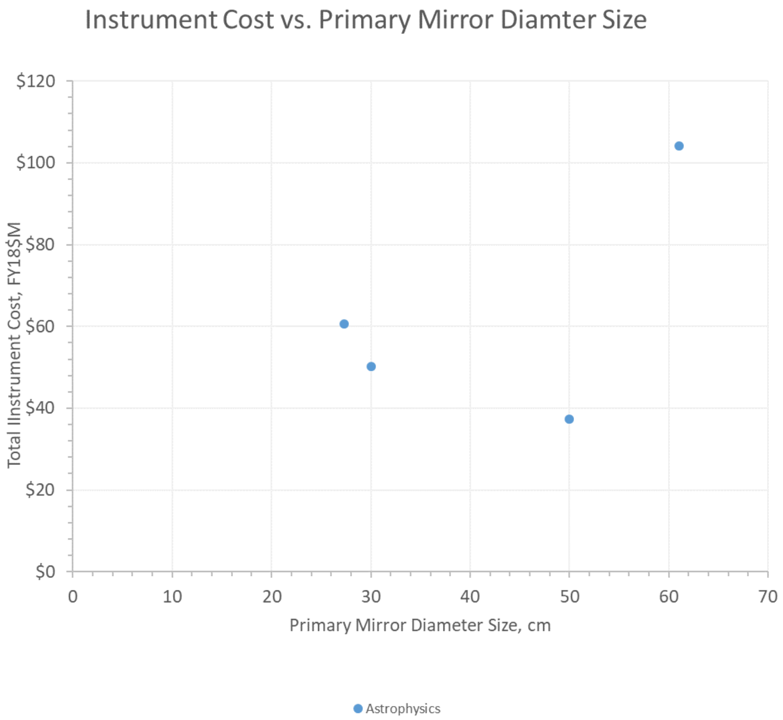


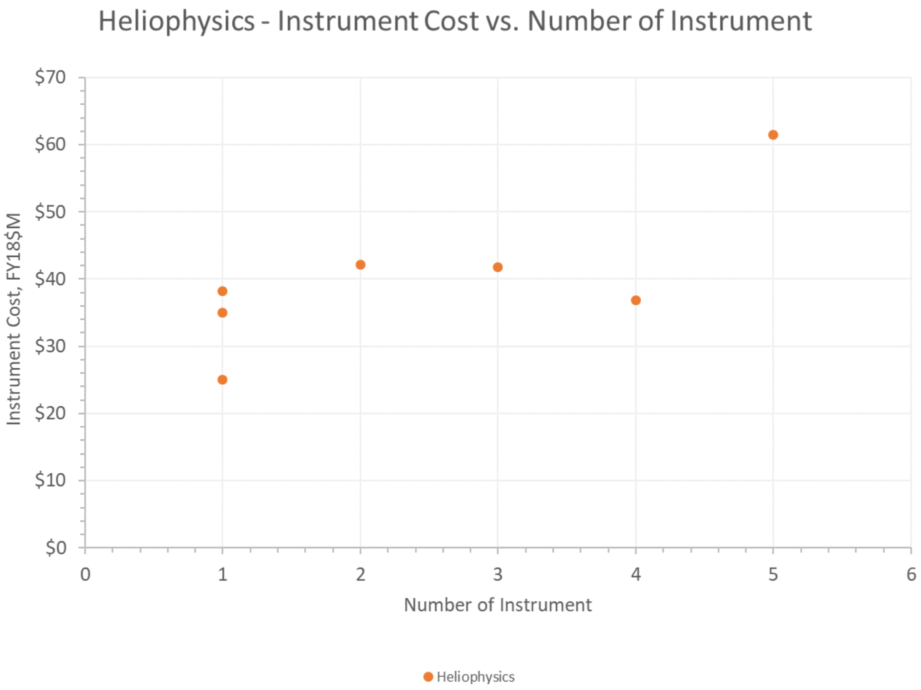
Cost vs. Instrument and Mission Type



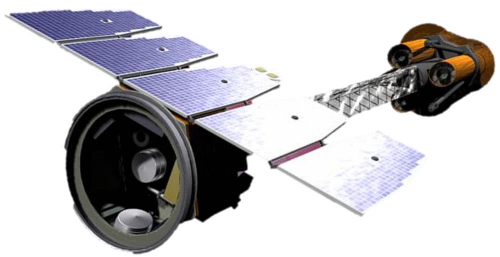


Astrophysics vs. Heliophysics Instrument Costs





Present – In Development

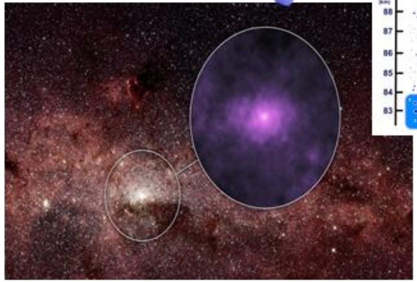


- Small Mission Explorer 14
- Imaging X-ray Polarimetry Explorer (IXPE)
  - Selected 2016
  - Currently in Phase B
  - Estimated Launch November 2020
  - “The Imaging X-ray Polarimetry Explorer (IXPE) exploits the polarization state of light from astrophysical sources to provide insight into our understanding of X-ray production in objects such as neutron stars and pulsar wind nebulae, as well as stellar and supermassive black holes. ” – from NASA Explorer’s program webpage
  - For more info: https://wwwastro.msfc.nasa.gov/ixpe/index.html

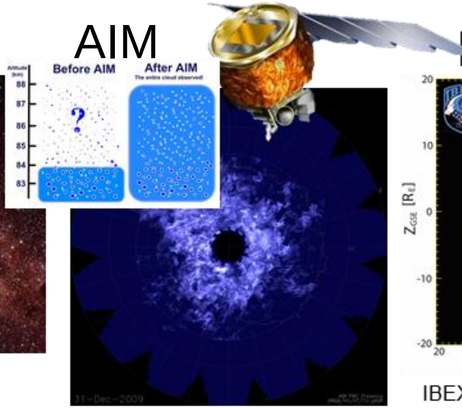
Present – Operation

SEMX Missions	Mission Type	Development B-D Duration (Months)	Planned Mission Duration (Months)	Final or Elapsed for mission currently in operation (Months)
NuSTAR	Astrophysics	36	24	75
AIM	Heliophysics	39	Data Not Available	136
IBEX	Heliophysics	33	24	118
IRIS	Heliophysics	37	24	62
RHESSI	Heliophysics	42	24	199

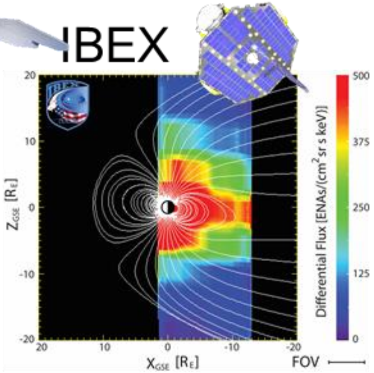
NuStar



X-Ray image of our Milky Way galaxy. The smaller circle shows the center of our galaxy where the NuSTAR image was taken.
Credits: NASA/JPL-Caltech

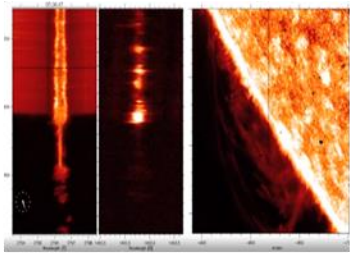


AIM captures noctilucent cloud cover above the Southern Pole
Credits: NASA/HU/VT/CU LASP



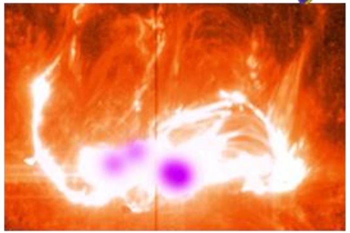
IBEX magnetospheric plasma sheet in profile . Shows the densest portions of the plasma sheets.
Credits: Southwest Research Institute/IBEX Science Team

IRIS



X-Ray image of our Milky Way galaxy. The smaller circle shows the center of our galaxy where the NuSTAR image was taken.
Credits: NASA/JPL-Caltech

RHESSI



Recording extreme temperature on the sun, RHESSI shows three hotspot (purple) superimposed on IRIS image. The two left are near surface, and dark spot is high above
Credits: NASA

Rules of Thumb (ROT)

- Total Mission Cost –to be “within family” of historic mission actuals, use the pie chart allocation by WBS and % as a ROT. Don’t forget to add cost reserve. Recommend 30%
- Payload instrument and Spacecraft will make up about half the entire PI-Managed budget (after reserve is accounted for)
- Astrophysics mission has one instrument (telescope)
- Heliophysics will have a range of 1-5 instruments (typically particles, mag. fields, etc..)
- Phase B-D development median schedule is approximately 37 months (~4 years with Phase A included and should be not longer or cost will overrun). Consider long lead items with tight schedule
- Average Phase E/F schedule for Astrophysics is ~74 months (planned ~24 months) vs. Heliophysics ~137 months (planned ~40 months). Astrophysics mission are short-lived compared to Heliophysics. Astrophysics telescope detectors have a short lifespan compared to Heliophysics type instruments
- Cryocoolers add more costs, and if needed, consider commercial cryocoolers with successful flight heritage or find left over spare hardware from other projects

Future - Enabling Low Cost Explorer Missions

Suggested approach and ways to achieve the $120M SMEX Cap

- Get experienced PIs and other core member from prior mission team for newly proposed science explorers. PI should be involved with mission management decision while keep focus on proposed science concepts and technologies
- Seek collaboration and partnership
- Small spacecraft that are commercially available are in the $10’s of millions
- Take lower risk on spacecraft (and higher risk with instrument)
- Rideshare. ESPA Grande (300kg) now costs about $8M (LEO) and $14M (GTO)
- Reduce the numbers of instruments (for Heliophysics missions)
- Partner with telescope vendors that has standardized telescopes for lower costs
- Be realistic during planning. Don’t be bias with involvement in project.

Summary

- Questions to self:
  - What’s the total average “low-cost” SMEX mission? *~$ 200M. Every single project had cost growth when planned (minimum 10%-~50%)*
  - What’s the average cost of spacecraft and instruments?
    - *Spacecraft - ~$50M*
    - *Instrument ~$60M for Astrophysics; and ~$40M for Heliophysics*
  - Changes of Cost, Mass and Power from PDR to launch? *Cost, Mass and Power has shown increased for the mission with records from PDR to Delivery.*
  - What’s the average “rapid” Development Schedule for Phase B-D? *Approximately 37 months on average.*
  - What are drivers for cost overruns? *New technology development, failure during testing, launch delays and re-testing*
  - What is considered to be “in-family” with respect to cost to previous actual missions? *~$190M for Astrophysics Mission and ~$200M for Heliophysics Mission*

References

- Paper
  - Elvis, Martin, “A Vigorous Explorer Program – submitted to the Astro2010 NAS/NRC Decadal Review of Astronomy and Astrophysics” (white paper) (Year not specified)
  - Watzin, James “SMEX LITE – NASA’s Next Generation Small Explorer” NASA GSFC, 1996
  - Principal Investigator-Led Missions in the Space Sciences, National Academies Press (April 22, 2006)
    - Chapter 5. PI-LED Mission Performance: Cost, Schedule, and Science
- Web
  - NASA’s official Explorer Program Page https://explorers.gsfc.nasa.gov/smex.html
  - NASA’s Astrophysics SMD https://science.nasa.gov/astrophysics
  - NASA’s Heliophysics https://science.nasa.gov/heliophysics
  - Explorers and Heliophysics https://ehpd.gsfc.nasa.gov/
  - NASA CADRe https://oncedata.msfc.nasa.gov/ contact Eric Plumer eric.plumer@nasa.gov or James Johnson james.k.johnson@nasa.gov

Caveats

- The ROT and guidance are intended to be used as a pre-phase A analysis
- The analysis and ROT were generated from high level data
- The data used from research are not normalized (data dive and vetted with the project's management, systems engineering and/or PI) after the retrieval from source
- The data sources are from CADRe and other resources such as scholarly published papers, articles, and journals

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The Jet Propulsion Laboratory

Dr. Tony Freeman, co-author

Mike DiNicola

Dr. Jairus Hihn

Dr. Alfred Nash

TeamX and The Innovation Foundry at JPL

Contact:

mchael.saing@jpl.nasa.gov

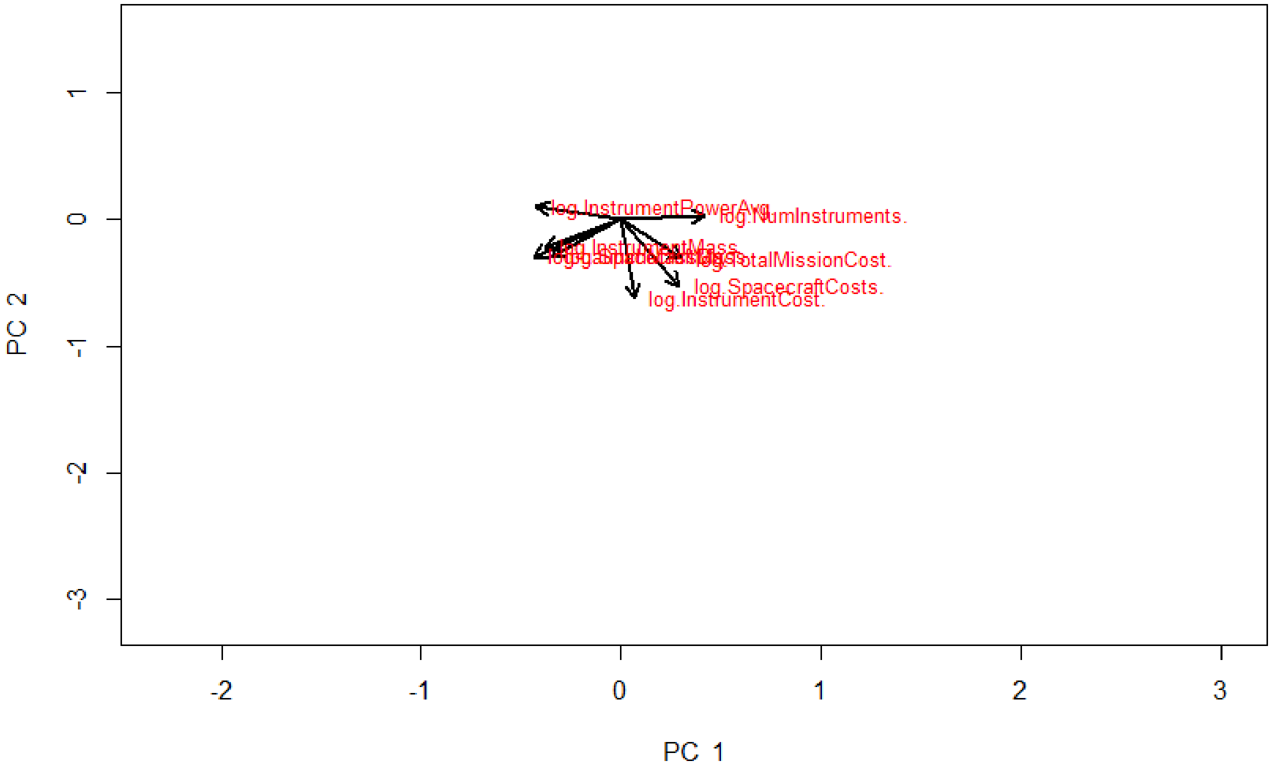
anthony.freeman@jpl.nasa.gov

Jet Propulsion Laboratory
California Institute of Technology

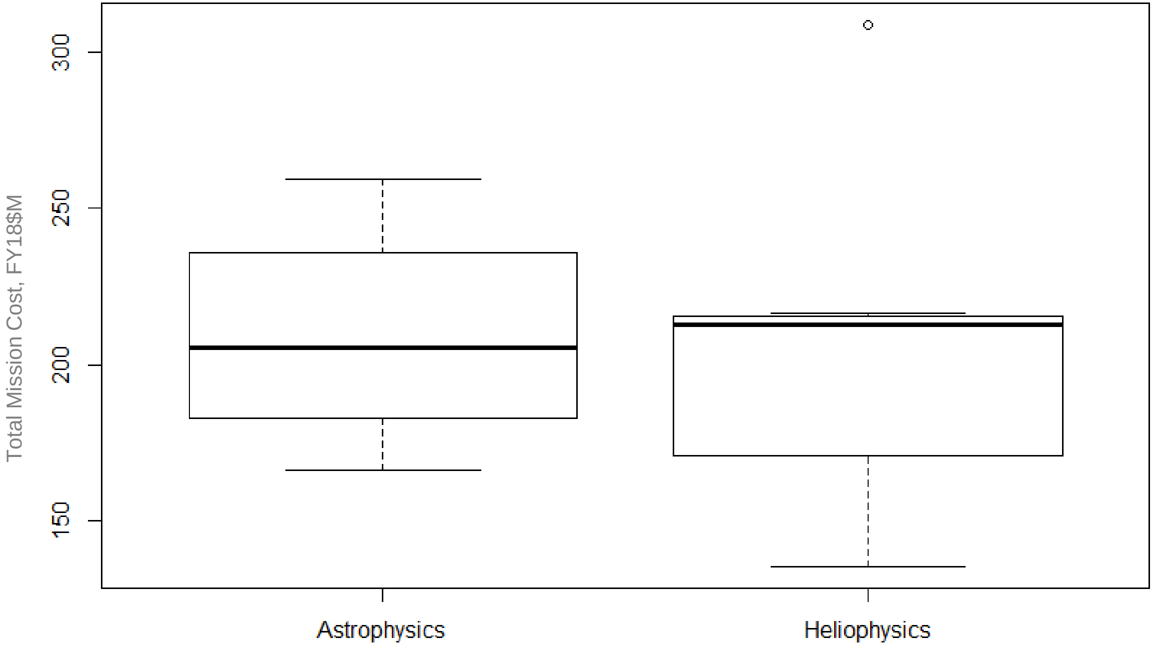
jpl.nasa.gov

Back-up

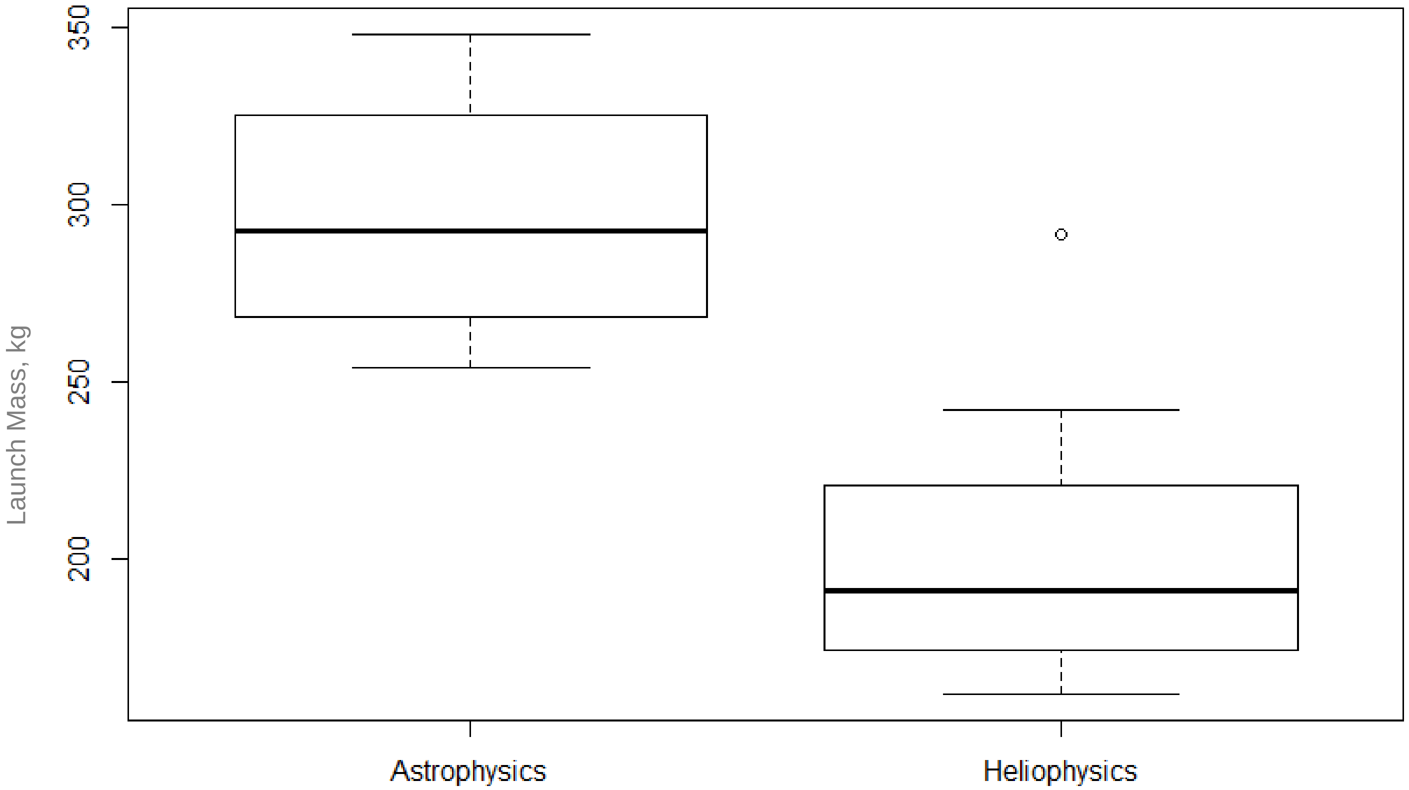
Cluster



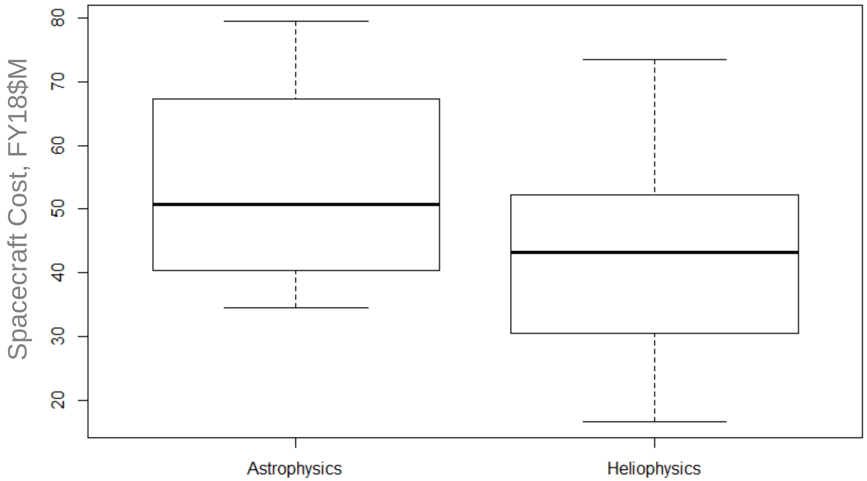
Total Mission Costs and

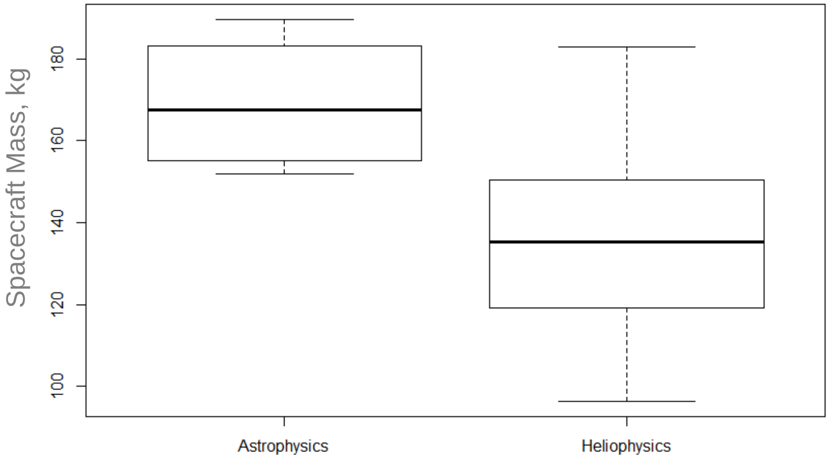


Total (Dry) Launch Mass



Spacecraft Costs and Launch Mass





Instrument Cost and Mass